

Using X-ray observations to identify the particle acceleration mechanisms in VHE SNRs and “dark” VHE sources

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Very high energy (VHE) γ -ray observations have proven to be very successful in localizing Galactic acceleration sites of VHE particles. Observations of shell-type supernova remnants have confirmed that particles are accelerated to VHE energies in supernova blast waves; the interpretation of the γ -ray data in terms of hadronic or leptonic particle components in these objects relies nevertheless strongly on input from X-ray observations. The largest identified Galactic VHE source class consists of pulsar wind nebulae, as detected in X-rays. Many of the remaining VHE sources remain however unidentified until now. With X-ray observations of these enigmatic “dark” objects one hopes to solve the following questions: What is the astrophysical nature of these sources? Are they predominantly electron or hadron accelerators? And what is their contribution to the overall cosmic ray energy budget? The paper aims to provide an overview over the identification status of the Galactic VHE source population.

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1 Introduction

Ground-based Cherenkov telescopes detect cosmic γ -rays in the *Very High Energy* (VHE, 100 GeV - 100 TeV) domain. In this frequency range, sources are visible in which charged particles are accelerated to TeV energies and beyond; those particles give rise to the detected γ -ray emission. The energetic particles can be confined inside the objects, close to the actual acceleration site, like in young shell-type supernova remnants (SNRs). In other cases, the particles diffuse out into the surrounding medium after their acceleration to high energies; in these cases, the size of the emitting region itself defines the extent of the “source” or object, like for example in a pulsar wind nebula (PWN).

The truly diffuse component of the high energy cosmic ray particles is predominantly being traced in the MeV-GeV domain, accessible to γ -ray satellites. Lower energy diffuse *electrons* are also traced through synchrotron emission in the radio band. At VHE energies, localized sources dominate because of their intrinsically harder particle spectra compared to the diffuse component.

A successful VHE survey of the Galactic plane became possible with the high sensitivity and large field of view (FoV) of the H.E.S.S. (High Energy Stereoscopic System) Cherenkov telescope system, with $F_{\min}(> 100 \text{ GeV}) \sim 4 \times 10^{-12} \text{ erg cm}^{-2} \text{ s}^{-1}$ for a 5σ point-source detection in 25 hrs, and a FoV of 3° FWHM (Aharonian et al. 2006c). The H.E.S.S. telescope system became operational end of 2003, and provides through its location in Namibia an excellent

view of the Galactic center region. The majority of the currently over 50 known Galactic VHE sources was discovered in the H.E.S.S. survey of the Galactic plane (Aharonian et al. 2005h, 2006g; Hoppe et al. 2007; Kosack et al. 2007), or in the H.E.S.S. FoV of observations of other targets in the Galactic plane (e.g. Aharonian et al. 2005c, 2007b).

Perhaps somewhat unexpectedly, many of the new VHE-emitting sources can not readily be identified with known astrophysical objects. Therefore, Galactic VHE astronomy does not only deal with the identification of particle acceleration mechanisms and efficiencies in well-known astrophysical objects, but also with the identification of sources which are so far “only” defined through their γ -ray emission. Follow-up observations of those sources with highly sensitive X-ray instruments such as *XMM-Newton* provide the very promising possibility to identify those enigmatic sources of high energy particles in our Galaxy.

2 The VHE – X-ray connection

Leptonic particles can be traced through synchrotron emission in ambient magnetic fields, in Galactic sources most notably in the radio and X-ray domains. Both, characteristic emission frequency and flux level depend on the B-field strength. If the non-thermal X-ray spectrum of an object can be attributed to synchrotron emission, then electrons with energies of $\sim 50 \text{ TeV}$ are being traced in typical interstellar magnetic fields of $3\text{--}5 \mu\text{G}$ (Aharonian et al. 1997). This electron population produces VHE γ -rays predominantly through Inverse-Compton (IC) scattering of ambient photons. In the TeV range, IC photon energies are of the same order as the upscattering electron energies. The minimum

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flux level is defined through the cosmic microwave background (CMB), higher IC flux levels can occur if far infrared (FIR) or stellar photon fields become relevant as target, either because of high surrounding fields or from the source itself. Only in special cases like the Crab Nebula, synchrotron photons provide the dominant IC target field (e.g. Aharonian et al. 2004a).

In typical interstellar B-fields, the corresponding peak energy fluxes in the VHE and X-ray band are of comparable magnitude. The sensitivities of current X-ray detectors such as *XMM-Newton* are therefore ideally suited to investigate VHE IC sources. Special care must however be taken if the VHE particle spectrum cuts off above ~ 10 TeV, because the corresponding peak of the synchrotron flux shifts into the soft X-ray and UV band, normally not accessible because of absorption in the Galactic plane. Moreover, as many VHE sources are extended beyond the $10'$ scale, only a fraction of the corresponding expected synchrotron flux can be mapped in a single X-ray telescope pointing. The B-field may not be constant throughout the VHE emitting region; in fact, in known VHE sources it is higher near the acceleration site, e.g. close to pulsar wind termination shock, with increased synchrotron emissivity there. Hence, *XMM-Newton*'s large FoV is an important feature to pin down the actual acceleration site of a VHE source.

Hadronic particles are visible in the γ -ray domain in nuclear collisions followed by π^0 -decay induced γ -ray emission. The photons typically carry $\sim 20\%$ of the primary energy (Kelner et al. 2006). If such an emission region is displaced from the actual particle acceleration site, this particle population is visible in X-rays only through synchrotron emission from *secondary* electrons, close to the sensitivity limit of current X-ray detectors. If particles are still being accelerated to high energies, then electrons are expected to be accelerated in conjunction with hadrons, with significant *primary* electron X-ray synchrotron emission. Especially in this latter case, the synchrotron spectrum provides a key diagnostic tool for the interpretation of the VHE emission.

Nonthermal Bremsstrahlung of energetic electrons can also be expected, both in the X-ray and the TeV energy range. In most scenarios however, Bremsstrahlung flux levels are below synchrotron and IC levels. There are cases where the interpretation of hard X-ray continuum emission in terms of either synchrotron or Bremsstrahlung is not unambiguous, leading to large differences in the respectively deduced electron energies, for example in Cassiopeia A (e.g. Vink 2005).

3 The Galactic VHE source catalog

Over 50 Galactic sources of VHE γ -ray emission are presently known. A comprehensive list of the sources can be found on the web¹.

¹ http://www.mpi-hd.mpg.de/HESS/public/HESS_catalog.htm,
<http://www.mppmu.mpg.de/~rwagner/sources/>, <http://tevcat.uchicago.edu/>

So far, four objects are identified as supernova remnant shells. RX J1713.7-3946 (Aharonian et al. 2004b, 2006a, 2007a) and RX J0852.0-4622 (Aharonian et al. 2005i, 2007d) are resolved in the VHE band, and the emission traces the respective SNR shells. RCW 86 (Hoppe et al. 2007a) is also resolved, with a VHE image matching the SNR shell. The γ -ray emission from Cassiopeia A (Aharonian et al. 2001, Albert et al. 2007a) is also attributed to its shell, though the object cannot be resolved in the VHE band.

The largest group of identified VHE sources consists of PWNe: The Crab Nebula (Weekes et al. 1989), and the H.E.S.S. detections G0.9+0.1, MSH 15-52, Vela-X, K3 in the Kookaburra complex, and HESS J1825-137 (Aharonian et al. 2005e, 2005g, 2006h, 2006e, 2005d). All but the first two PWNe are spatially resolved in the VHE band. The objects are clearly identified because of an association with a pulsar and a matching X-ray synchrotron nebula.

PWN processes also play a role in some γ -ray binaries. This object class consists of point-like and variable VHE sources, where the light curves match those from the corresponding high mass X-ray binary systems. Examples are PSR B1259-63, LS 5039, and LSI 61-303 (Aharonian et al. 2005b, 2005f, 2006f; Albert et al. 2006b). The nature of the compact object is not certain in the latter two objects.

Recently, VHE emission coincident with the stellar cluster Westerlund 2 was detected (Aharonian et al. 2007e), opening up the possibility that VHE particle acceleration may take place in collective phenomena such as stellar winds. The nature of the acceleration process is however not yet certain. In general, identification in the context here means that the γ -ray emission is associated with a counterpart identified in lower frequency bands. An identification of the actual particle acceleration process and its exact location inside the object is not required at this stage.

For several newly detected VHE sources, an identification with a lower frequency band object has been suggested based on positional proximity and energetic arguments. After some remarks on identified SNR shells and PWNe, some associations where one of these scenarios is likely fulfilled will be discussed. For few objects, an association of an extended VHE object with an X-ray binary has been suggested, but the situation in those cases is less clear.

4 Shell-type supernova remnants

All shell-type VHE SNR are young, and are also emitters of non-thermal X-rays. The VHE emission unambiguously traces VHE particles in the shells, which are presently being accelerated to these high energies. However, despite the fact that spectra for the bright SNRs range from 150 GeV to above 50 TeV, the lever arm is not large enough to unambiguously decide whether the particles are hadrons or leptons. The classical hadronic E^{-2} -type spectra can be modified at the high energy end through particle escape, and overall through nonlinear acceleration effects, making a distinction between leptonic and hadronic spectra difficult.

X-ray data of these SNRs can be used in two steps: Firstly, the width of thin synchrotron-emitting filaments can be used to determine the B-field in the emission region, as the determined length scale is commonly being linked to synchrotron cooling (e.g. Vink & Laming 2003, Völk et al. 2005). Such derived B-fields exceed the shock-compressed interstellar B-field values by far and are typically above $100 \mu\text{G}$ for young SNRs. Secondly, using the such derived B-fields and the total synchrotron flux, the expected IC emission of the SNR can be calculated. While $\sim 10 \mu\text{G}$ -sized fields could explain the detected VHE γ -ray emission in the VHE-emitting shells as IC radiation, in $\sim 100 \mu\text{G}$ -sized fields the expected IC flux is by far lower than the detected VHE flux, unless morphological patterns like small magnetic field filling factors affecting the synchrotron emissivity (e.g. Lazendic et al. 2004) would be invoked. Therefore, in SNR models it is concluded that the VHE emission is of hadronic origin (Berezhko et al. 2003, 2006, 2007).

To determine the flux of the hadronic cosmic ray particles in the source, the target gas density needs to be known. Thermal X-ray emission as detected in some young SNR can provide valuable information on the shock-heated gas. However, for all SNRs detected in VHE emission, the environment seems strongly influenced by the particle wind of the progenitor star. In such wind bubble setups, it has been argued that the gas heating may yet be suppressed. Moreover, thermal equilibrium may not have been reached, affecting the determination of the emitting gas density. Special care must therefore be taken when interpreting the gas density, in particular the limits thereof in RX J1713.7-3946 and RX J0852.0-4622.

5 VHE pulsar wind nebulae

Young pulsars like the Crab pulsar convert $\sim 50\%$ of their spin-down luminosity into accelerated particles. This population is usually assumed to be dominated by leptons that were created in the Poynting-flux dominated pulsar wind. The particles are redistributed in energy and accelerated to high energies at a termination shock and radiate unpulsed synchrotron emission in the B-field also formed in the wind, as well as IC emission.

In compact nebulae with high B-fields as the Crab Nebula ($\sim 160 \mu\text{G}$, Aharonian et al. 2004a), the synchrotron flux strongly exceeds the IC flux, despite an additional contribution to the IC target field from synchrotron photons. In middle-aged PWN, X-ray and VHE energy fluxes are comparable, and the data can be used to constrain the B-field and/or the target photon fields (FIR and stellar fields). Examples are Vela-X and MSH 15-52, which exhibit a similar VHE and X-ray morphology.

In the case of HESS J1825-137, the associated X-ray nebula G18.0-0.7 detected with *XMM-Newton* (Gaensler et al. 2003) is much more compact than the VHE nebula. An identification of the two sources was nevertheless possible because of the common offset direction of both nebulae

from the powering pulsar, together with spectral imaging of the H.E.S.S. source (Aharonian et al. 2006b). The different sizes can be explained in a “relic” PWN scenario by the larger lifetime of the IC-emitting VHE particles, compared to the higher-energy synchrotron-emitting (and thus cooling) particles (Aharonian et al. 1997). The fact that the nebula is expanding asymmetrically can be explained in a “crushed” PWN scenario like in Vela-X (Blondin et al. 2001) by the interaction with an asymmetrically evolving SNR reverse shock. In general, ISM density gradients might cause such an effect even in a non-SNR environment. The offset of the VHE peak intensity from the pulsar ($\sim 0.3^\circ$) can be related to a higher injection efficiency of the pulsar in the past.

Comparing the pulsar population to the H.E.S.S. Galactic plane survey, it turns out that energetic pulsars are indeed very likely associated with VHE emission (Aharonian et al. 2007c). For some VHE sources, the probability for a chance coincidence with an energetic pulsar is reasonably low to identify the sources as *VHE PWN candidates*, even without the detection of a synchrotron nebula. Examples are HESS J1718-385, HESS J1809-193, and HESS J1912+101 (Aharonian et al. 2007c, Komin et al. 2007, Hoppe et al. 2007b). For HESS J1809-193, *Chandra* data have meanwhile indeed revealed the existence of an X-ray PWN around the corresponding pulsar (Kargaltsev & Pavlov 2007).

6 “VHE composite” supernova remnants

Several H.E.S.S. survey sources are positionally coincident with radio SNRs. For those, a unique identification with the shells is however not possible based on the VHE and radio data alone. For HESS J1813-178 and HESS J1640-465, the SNR shells G12.8-0.0 (Brogan et al. 2005) and G338.3-0.0 (Whiteoak & Green 1996) are too compact to be resolved in the VHE band. Those remnants were however easily investigated in single *XMM-Newton* pointings (Funk et al. 2007b, 2007a). Surprisingly, the *XMM-Newton* data revealed new PWN candidates inside the shells, whereas no X-ray emission was detected from the shells themselves. The PWN candidates were unexpected because no radio pulsars are known inside the remnants. The identification of the X-ray sources as PWN seems nevertheless plausible because of their morphology and SNR location. *Chandra* follow-up observations of the PWN candidate inside HESS J1813-178 have been performed in the mean time with the aim to confirm the PWN nature (Helfand et al. 2007).

The data establish G12.8-0.0 and G338.3-0.0 as composite SNRs. Because the VHE emission cannot be unambiguously identified with either the respective SNR shell or PWN yet, one might label them “VHE composites” for now.

Also HESS J1804-216 can be similarly classified. In this case however, the radio SNR (W30, Kassim & Weiler 1990) is much more extended than the VHE source, which might morphologically be associated with part of the (not well defined) shell or with the SNR interior. The X-ray PWN

around PSR B1800-21 as detected with *Chandra* represents a plausible counterpart (Kargaltsev et al. 2007a, 2007b). However, as the proper motion of the pulsar (Briskin et al. 2006) disfavors its association with W30, other PWN (without radio pulsars) could be present inside W30. Indeed, a *Suzaku* pointing on the center of the H.E.S.S. source has revealed another possible, albeit yet unidentified X-ray counterpart (Bamba et al. 2007). Nonetheless, *XMM-Newton* data might be required to achieve sufficient coverage of the VHE source to identify all possible counterparts, and to examine the faint extended PWN around PSR B1800-21 (or other PWN candidates) to allow for a morphological association between the X-ray and VHE source. Also, the connection of the VHE particles to the Northern SNR shell, which based on ROSAT data was identified as a thermal X-ray emitter (Finley & Oegelman 1994), is an attractive target for *XMM-Newton* investigations.

7 “Dark” VHE sources

Several VHE sources entirely lack plausible counterparts in lower energy bands, and have therefore been called “dark” VHE sources (Aharonian et al. 2005h, 2006g; Kosack et al. 2007). Physically, a “dark” VHE emitter might either be purely driven by hadronic emission (though some level of synchrotron emission is inevitably expected from secondary electrons if the γ -rays are produced in hadronic collisions), or by exotic processes (such as dark matter emission).

Matsumoto et al. (2007) argue that the X-ray limit achieved in a deep *Suzaku* exposure of HESS J1616-508 excludes a leptonic scenario for any plausible B-field, and call the VHE source “dark”. On the other hand, the energetic pulsar PSR J1617-5055 represents a possible counterpart in an offset PWN scenario (Aharonian et al. 2006g, Landi et al. 2007). Here, the expected X-ray synchrotron emission depends on the extrapolation from the UV band that corresponds to the VHE IC flux, and the limited *Suzaku* FoV might not have covered the entire VHE-emitting region. Even PSR J1614-5048 might power (part of) the source, though this scenario is challenging because of the high required conversion efficiency of spin-down to VHE luminosity of $\sim 10\%$, and the large angular offset. Further investigations are hence required to clarify the nature of HESS J1616-508.

It was argued by Yamazaki et al. (2006) that the absence of significant X-ray emission may be a signature for old but still VHE emitting SNRs. Significant VHE emission from hadronic particles could still be expected, either from the shell or from particles encountering nearby molecular clouds, whereas primary electrons are not any more energetic enough to emit X-ray synchrotron radiation. The X-ray emission may therefore be dominated by secondary electrons, with TeV to X-ray flux ratios (expressed as $R_{\text{TeV/X}} = F_{\gamma, 1-10 \text{ TeV}}/F_{\text{X}, 2-10 \text{ keV}}$) of ~ 100 or more, compared to young SNRs with values of less than ~ 2 .

Nonetheless, other object types may also exhibit such large TeV to X-ray flux ratios, therefore further broadband

data are needed in each case to establish the nature of individual VHE sources.

8 Possible interaction with molecular clouds

Molecular clouds merely serve as targets of energetic particles, whereas the actual acceleration site may be disconnected from the emitting cloud. A prominent example for such a scenario is the diffuse VHE emission from the Galactic ridge near the Galactic center (Aharonian et al. 2006d).

A good signature for such a scenario is the close spatial correlation between VHE and CO/CS emission tracing molecular gas. VHE emission detected with H.E.S.S. close to SNR W28, which is indeed coincident with CO emission located in a distance similar to the SNR, might be caused by particles that were accelerated in W28 (Rowell et al. 2007). Similar scenarios could explain the emission from MAGIC J0616+225 inside IC 443 (Albert et al. 2007c), and HESS J1834-087 coincident with the interior of the SNR W41 (Albert et al. 2006a). The faint flux level possibly detected with *XMM-Newton* from HESS J1834-087 is compatible with secondary electron emission (Tian et al. 2007).

9 Prospects for XMM-Newton observations

The high sensitivity and large FoV of *XMM-Newton* make this instrument ideally suited for the investigation of VHE γ -ray sources. The large FoV is required to identify previously unknown objects such as the PWN candidates described earlier. Jointly with VHE detectors, *XMM-Newton* will thus probe the population of radio-dim pulsars. *Chandra* can effectively be used to detect compact PWN; however, those objects are likely influenced by the pulsar geometry or motion and do not reflect the large-scale propagation of electrons that give rise to the VHE emission. *XMM-Newton*'s sensitivity is required to trace those extended and offset nebulae in low B-field environments. Also the number of VHE-emitting SNR shells is expected to grow, and the FoV and sensitivity of *XMM-Newton* will be needed to pin down the nature of the VHE particles, both through primary and secondary electron emission. The discovery potential for new sources or even new source types in case of “dark” VHE source observations is large.

Together with the new VHE instruments in the Northern Hemisphere that have recently come online (MAGIC, VERITAS), with H.E.S.S. and its extension to higher sensitivity and lower energy threshold (H.E.S.S. phase II), and with the next generation of instruments such as CTA² that could start operation early in the next decade, the continuous availability of *XMM-Newton* will provide indispensable input for the understanding of the high energy particle accelerators in our Galaxy.

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² <http://www.mpi-hd.mpg.de/CTA>

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